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Solar powered steam-methane reformer economics

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Abstract

With funding from the U.S. Department of Energy (DOE) and SolarThermoChemical LLC, PNNL is developing a solar-powered steam-methane reformer (SMR). The reformer sits at the focal point of a parabolic dish concentrator, with the concentrated solar energy providing the endothermic heat of reaction. The result is a syngas comprising mostly H₂ and CO with a heating value approximately 27% higher than the entering natural gas.

On-sun testing completed in 2013 achieved a solar-to-chemical energy conversion efficiency as high as 69%, based on the ratio of incremental chemical energy created to direct normal insolation striking the parabolic dish concentrator. Advanced designs are expected to improve upon this performance. Details regarding the design and performance of the solar reformer are presented elsewhere.

This paper describes the projected economics of the parabolic dish SMR system. The key metrics are the levelized cost of electricity for a modified, combined-cycle power plant that operates with natural gas or syngas from the dish SMR, and the levelized cost of chemical energy based on the incremental chemical energy produced in the SMR. The latter can be compared to the levelized cost of natural gas over the life of the solar-powered system. Initial capital and annual maintenance cost estimates for each system component are also presented.

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1. Introduction

Several decades in development, concentrating solar thermal power technology is on the verge of becoming a mainstream electric power generating option in areas with high annual DNI like the Southwestern United States. Still, further improvement in CSP technology is required to achieve the above goal, particularly in the U.S, where abundant and inexpensive natural gas makes it difficult for CSP to compete with natural gas-fired combined-cycle power plants. This paper describes the potential cost, performance, and economic characteristics of a CSP technology that will not only compete with natural gas, but could be substantially better.

Nomenclature

CC	combine-cycle
CSP	concentrating solar (thermal) power
DLN	dry low NO _x
DNI	direct normal insolation
DOE	Department of Energy
ITC	investment tax credit
kW	kilowatt-electric
kWt	kilowatt-thermal
LCOE	levelized cost of electricity or energy
NG	natural gas
NGCC	natural gas combined cycle
PNNL	Pacific Northwest National Laboratory
SMR	steam-methane reformer

2. The technology

Using solar energy to drive the reformation of methane and steam to syngas (CO and H₂) is not a new concept, but still a worthy one. Current and prior solar thermal electric power plants, including fossil-solar hybrids, have all been limited by the energy conversion efficiency possible with steam-Rankine heat engines. No practical solar systems have yet been developed for heating compressed air to the temperature required by the most efficient gas turbines. Thus, CSP must not only compete with inexpensive natural gas, but also bears the burden of a less efficient energy conversion cycle.

By definition, CSP alone produces an inferior product compared to natural gas. Moderate temperature (≈ 600 °C) thermal energy, whatever the medium, has much lower energy density than natural gas and is gradually lost over time if stored. However, its greatest comparative deficiency is its lower exergy. Chemical energy (whether natural gas, syngas, or some other combustible fluid) is readily converted to electricity via combined Brayton and Rankine cycle power plants at much higher efficiency than possible with a Rankine cycle alone. Parabolic dish concentrators, always pointing directly toward the sun, have a much higher annual average efficiency than any other concentrator. This efficient use of expensive reflective surface also provides a significant economic advantage.

The steam-methane reforming reaction is highly endothermic. The chemical energy content of the syngas product is 27% higher than in the natural gas reactant. Thus, by providing a mechanism for converting solar insolation into chemical energy, a solar-powered steam-methane reformer provides the key to cost-effective CSP compared to a CC plant operating on natural gas alone. Prior solar SMR systems have been too inefficient and/or too costly. More efficient (up to 69% DNI conversion to chemical energy in field testing to date) and less costly

solar powered SMR technology is being developed at PNNL to make fossil-solar hybrid power plants more broadly cost-effective.

3. Solar SMR development at PNNL

Although several different concentrators could be used, development of a solar powered SMR at PNNL has utilized a parabolic dish. While heliostats focused on a central SMR would provide SMR size economies-of-scale, a parabolic dish offers the benefits of production volume economies-of-scale and results in a system that is no more costly per unit capacity for a single dish than for a field of dishes large enough to provide syngas to a utility-scale NGCC power plant. In fact, the per unit capacity cost for a single dish will actually be lower because natural gas, water, and syngas piping costs will be significantly less. In addition, smaller dish fields would be applicable to industrial and commercial settings where the price of natural gas is higher, making the solar dish SMR even more economically attractive. Nevertheless, current development is directed toward utility-scale power production per the interests of the U.S. Department of Energy's Sunshot Initiative. Details regarding the design and testing of the PNNL solar SMR are presented in another paper in this Energy Procedia authored by Robert Wegeng.

4. NGCC power plant characteristics

Cost and performance characteristics for a utility-scale, NGCC power plant were taken from a report prepared by the U.S. Department of Energy's National Energy Technology Laboratory and a subsequently published update [1, 2]. These characteristics are presented in Table 1. Cost data in Table 1 are in 2011 U.S. dollars. These costs were updated to 2012 dollars prior to making the levelized cost of electricity calculations described below.

Table 1. NGCC Power Plant Cost and Performance Assumptions

Total "Overnight" Construction Cost, \$M	\$404
Fixed Annual Maintenance Cost, \$M/year	\$6.77
Variable Maintenance Material Cost, \$/MWh	\$1.14
Variable Consumable Supplies Cost, \$/MWh	\$0.68
Combustion Turbine Power Output, MW	362
Steam Turbine Power Output, MW	203
Parasitic Power Consumption, MW	10
Net Power Plant Power Output, MW	555
Net Power Plant Heat Rate, Btu/kWh	6,798

5. Solar SMR system characteristics

Cost and performance characteristics for a parabolic dish SMR plant, sized to provide the maximum syngas solar fraction ($0.27/1.27 = 0.21$) to the above combined-cycle power plant at noon on summer solstice, are presented in Table 2. Cost data in this table are in 2012 U.S. dollars. The concentrator cost was based on an estimate provided by Infinia Corporation for their latest parabolic dish model, the PowerDish™ V. The SMR cost was based on manufacturing studies recently completed by PNNL in parallel with the prototype testing noted above. NG, water, and syngas field piping requirements were determined by developing a layout for the required field of parabolic dish SMR units and sizing each pipe segment for its unique flow rate. Typical natural gas distribution piping costs per foot of pipe, as a function of diameter, were applied to the field piping design to estimate piping costs.

Concentrator maintenance cost data described in Kolb et al. for heliostats were adapted for the parabolic dish [3]. The resulting sum of concentrator washing and other maintenance costs equals $\$1/\text{m}^2$ of concentrator aperture area

per year. Routine maintenance for the SMR and associated syngas/reactant heat exchanger is expected to be limited to its instrumentation and controls. This was estimated to cost three times the non-washing maintenance cost for the concentrator or \$2/m². However, the SMR and heat exchanger lives are uncertain at this point. The levelized cost analysis assumed the SMR would need to be refurbished every 10 years and the heat exchanger every 15 years. The refurbishments were assumed to cost one-third and one-half the original cost (in real dollars) for the SMR and heat exchanger, respectively. The higher fraction for the heat exchanger reflects its higher fraction of labor and tooling compared to the cost of its material. Finally, the maintenance cost for the collector field piping was assumed to be 2% of its initial capital cost per year.

Table 2. Solar SMR System Cost and Performance Assumptions

Concentrator Field, \$/kW DNI	\$175
SMR, \$/kW DNI	\$140
Syngas/Reactant HX, \$/kW DNI	\$60
NG piping, \$/kW DNI	\$13
Water piping, \$/kW DNI	\$13
Syngas piping, \$/kW DNI	\$14
Water supply and pump, \$/kW DNI	\$5
Total "Overnight" Construction Cost, \$/kW DNI	\$420
Annual DNI Conversion to Chemical Energy	0.70
Peak DNI Basis	1 kW/m ²
Annual DNI Basis	Phoenix, AZ

6. Syngas impacts

General Electric (GE) has recently developed a combustion turbine for the integrated gasification combined-cycle (IGCC) market, with or without CO₂ capture, and literature describing the performance of this turbine was obtained from GE's web site. The GE 7FA Syngas turbine has a capacity of 232 MW compared to 211 MW[†] for the 7FA natural gas-fired turbine and an LHV efficiency of 41% compared to 38.5% for the NG-fired turbine in a simple cycle application. The combined cycle advantage is even greater, with the syngas-fired combined cycle plant having a rated LHV efficiency of 67.9% compared to 57.5% for the NG-fired CC system.

The typical syngas produced by coal-fired IGCC has a lower H₂ to CO ratio than syngas from natural gas. In addition, our proposed solar-natural gas hybrid plant would require the combustion turbine to function well with a gas composition that would vary from natural gas to syngas including the range of mixtures between these two endpoints.

Discussions with GE identified differences in the fuel combustion systems used for coal-based syngas and natural gas. The former uses a diffusion flame combustor with diluent added for NO_x abatement. In an IGCC plant, nitrogen from the air separation unit is used as the diluent. Dry low NO_x (DLN) combustors are usually used for natural gas. Nitrogen will not be available as a diluent at the solar hybrid combined-cycle plant, of course, but there is no apparent reason why DLN technology could not be used with syngas.

Combustion turbine cost estimates presented in the NETL report cited above for coal-based syngas, with and without water-gas shifting of CO to H₂ are more expensive than the cost estimate for a combustion turbine operating

[†] Note that the natural gas-fired combined cycle power plant referenced in this study uses an earlier version of the GE 7FA combustion turbine that had a rated output of only 181 MW per unit.

on natural gas, but the gross power output of the combustion turbines operating on syngas is significantly higher, hence the cost per kW is lower.

At this point it is unclear what the impact on turbine cost and performance will be to allow combustion of a fuel stream that varies in composition from natural gas to syngas and all possible mixtures between these two endpoints. These issues will be addressed in 2014 via consultations with GE or another utility-scale combustion turbine vendor. For the analysis presented here, the combined cycle power plant cost, capacity, and efficiency were assumed to be invariant with fuel gas composition.

7. Economic assumptions and LCOE results

The data in Tables 1 and 2 were combined with the economic assumptions listed in Table 3 to calculate several LCOE figures of interest. Natural gas prices were assumed to match the current Baseline forecast by the U.S. Department of Energy [4]. The LCOE results, shown in Table 4, are expressed in real 2012 dollars.

The LCOE was calculated to be \$0.058/kWh for NGCC and NG/solar SMR CC power plants when the currently available 30% ITC was applied to the solar portion of the hybrid power plant. Elimination of the ITC only raised the hybrid plant LCOE to \$0.059/kWh because the solar fraction of annual energy input is only about 5%. The annual fraction is reduced from the 21% possible at design conditions (solar noon on Summer solstice) because the annual average DNI per m² is much less than the 1kW/m² at the design point and conversion efficiency declines at lower DNI levels because of fixed thermal losses from the reactor. Conversion of syngas to methanol is being considered for future versions of the solar system. By adding methanol storage, the solar fraction possible rises to near 20%. A more telling economic comparison is between the levelized costs of NG and the solar fraction of the syngas energy. The NG LCOE is \$6.62/MMBtu while the solar portion of the syngas LCOE is \$5.24/MMBtu with the ITC and \$7.49/MMBtu without the ITC.

8. Discussion

The analysis described above has shown the cost of chemical energy produced by a parabolic dish SMR system could be less than current and projected NG prices in the U.S., assuming the current 30% solar ITC still applies when the hybrid plant is constructed. The LCOE for a CC power plant is essentially the same whether running on NG or a varying mixture of solar SMR syngas and NG. Given that natural gas prices in the U.S. are at all-time lows in real dollars, the upside potential of this technology seems very good.

The greatest uncertainties at this point in the development process are the annual conversion efficiency (assumed to be 70% DNI to chemical energy in this analysis) and longevity of the SMR, which will have to be determined over longer testing periods than have been conducted to date. Testing of the next generation prototype is planned for 2014. The cost and performance impacts of varying the combustion turbine fuel composition must also be determined.

Table 3. LCOE Calculation Economic Assumptions

Item	Assumption
First Year of Plant Operation	2018
Plant Economic Life, years	30
Combined Cycle Depreciable Life, years	20
Simple Cycle Depreciable Life, years	15
Solar Depreciable Life, years	5
Solar Investment Tax Credit Rate	0%, 30%
Property Tax and Insurance Rate, %, non-solar	2%
Property Tax and Insurance Rate, %, solar	1.25%
Income Tax Rate, %	38%
Equity Fraction	50%
Nominal Equity Rate	9.62%
Nominal Debt Rate	5.90%
Nominal Pre-Tax Discount Rate	7.76%
Nominal After-Tax Discount Rate, %	6.64%
General Inflation Rate, %	3%
NG or Solar-NG Hybrid Power Plant Capacity Factor	0.85
Startup Cost, % of Construction Capital	2%
Working Capital, % of Annual O&M and Fuel	25%

Table 4. LCOE Results

NGCC Power Plant	\$0.0581/kWh
NG-solar SMR hybrid Power Plant with ITC	\$0.0575/kWh
NG-solar SMR hybrid Power Plant without ITC	\$0.0585/kWh
NG fuel only	\$6.62/MMBtu
Solar portion of syngas energy with ITC	\$5.24/MMBtu
Solar portion of syngas energy without ITC	\$7.49/MMBtu

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